

Recent Developments on the Studies of Thunderstorm and Geomagnetic Storm events

DHEP Annual Meeting

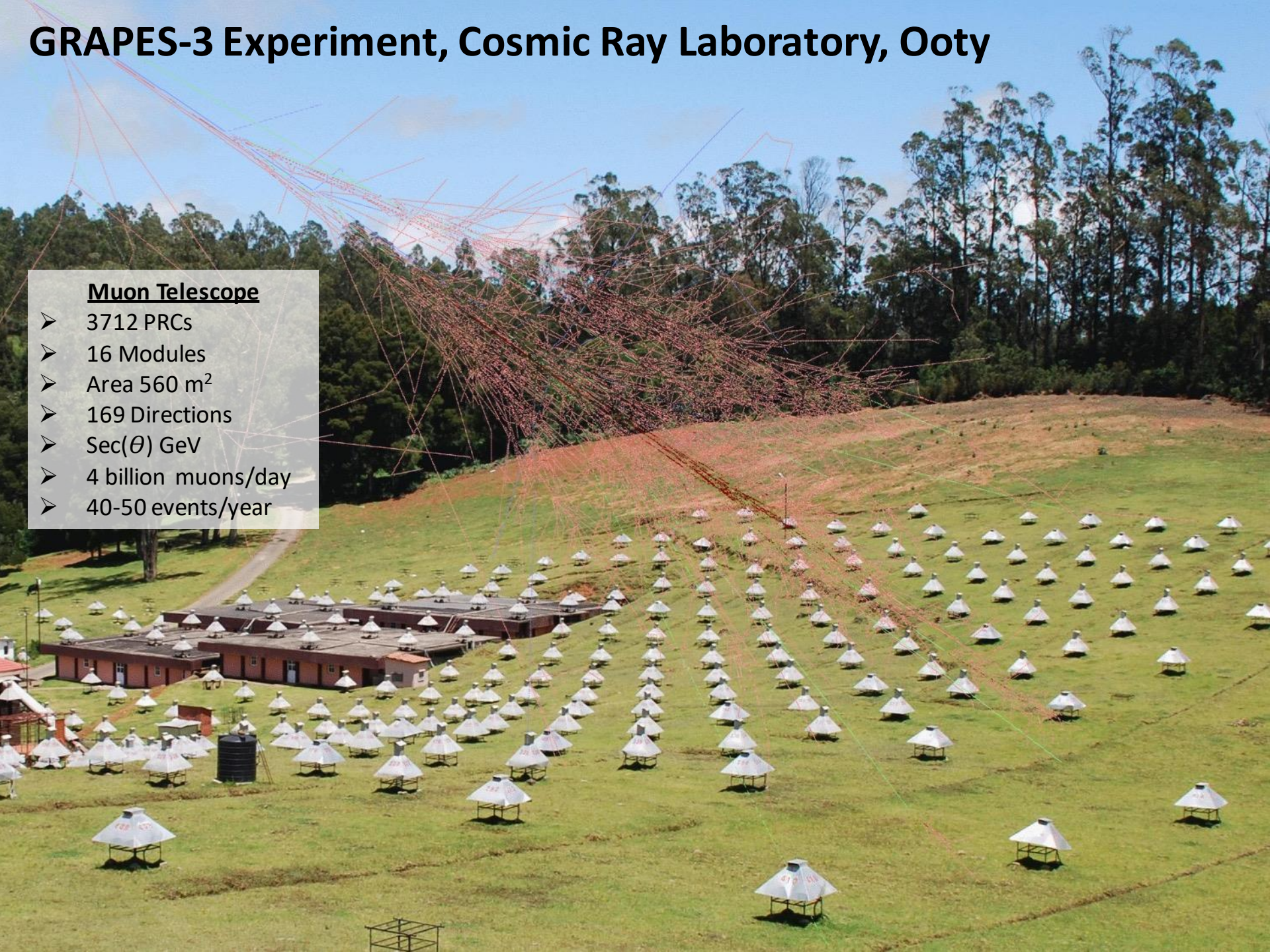
B. Hari Haran

Part I: Thunderstorm Events

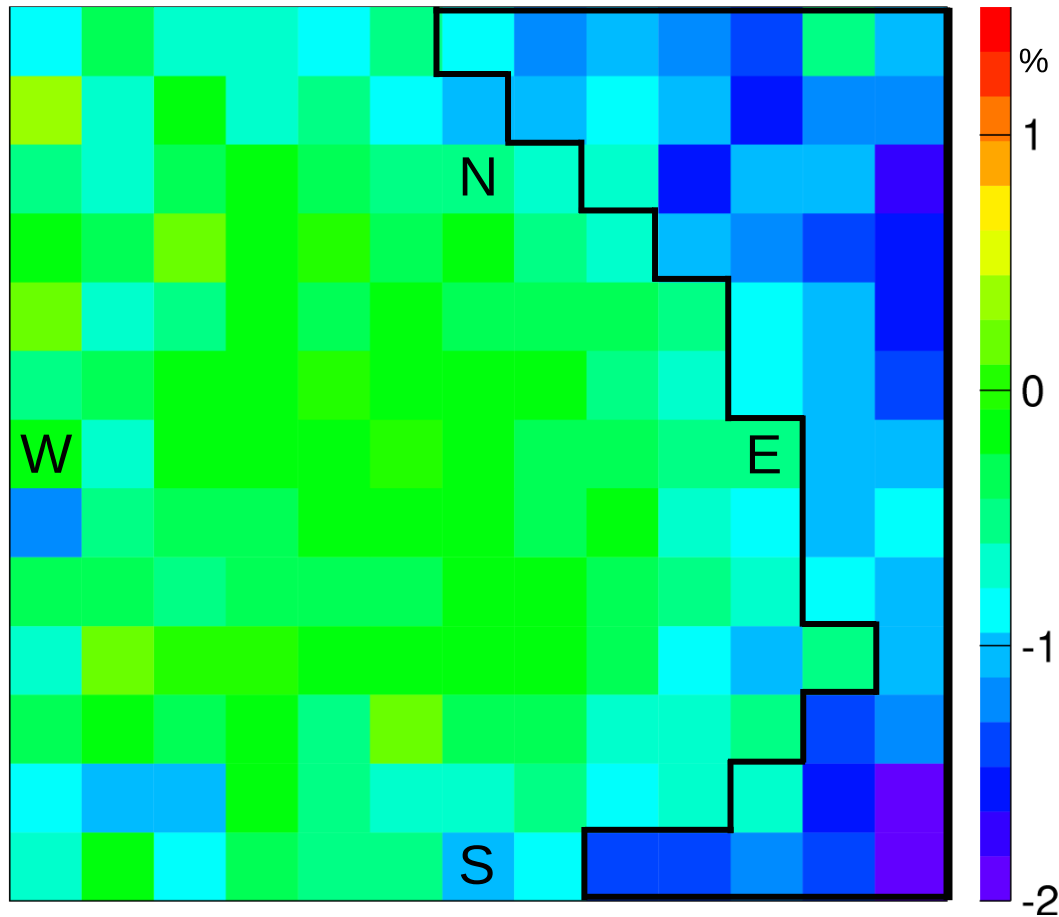
GRAPES-3 Experiment, Cosmic Ray Laboratory, Ooty

Muon Telescope

- 3712 PRCs
- 16 Modules
- Area 560 m²
- 169 Directions
- Sec(θ) GeV
- 4 billion muons/day
- 40-50 events/year

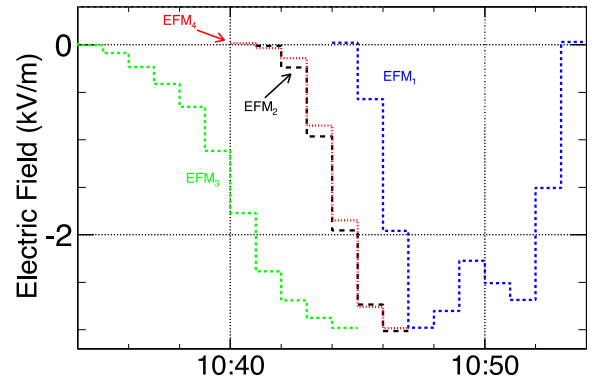
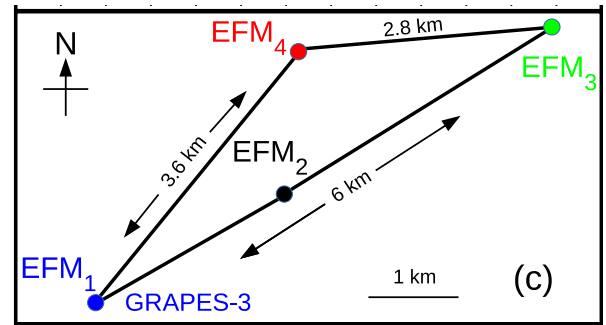


Muon Image of 1 Dec 2014

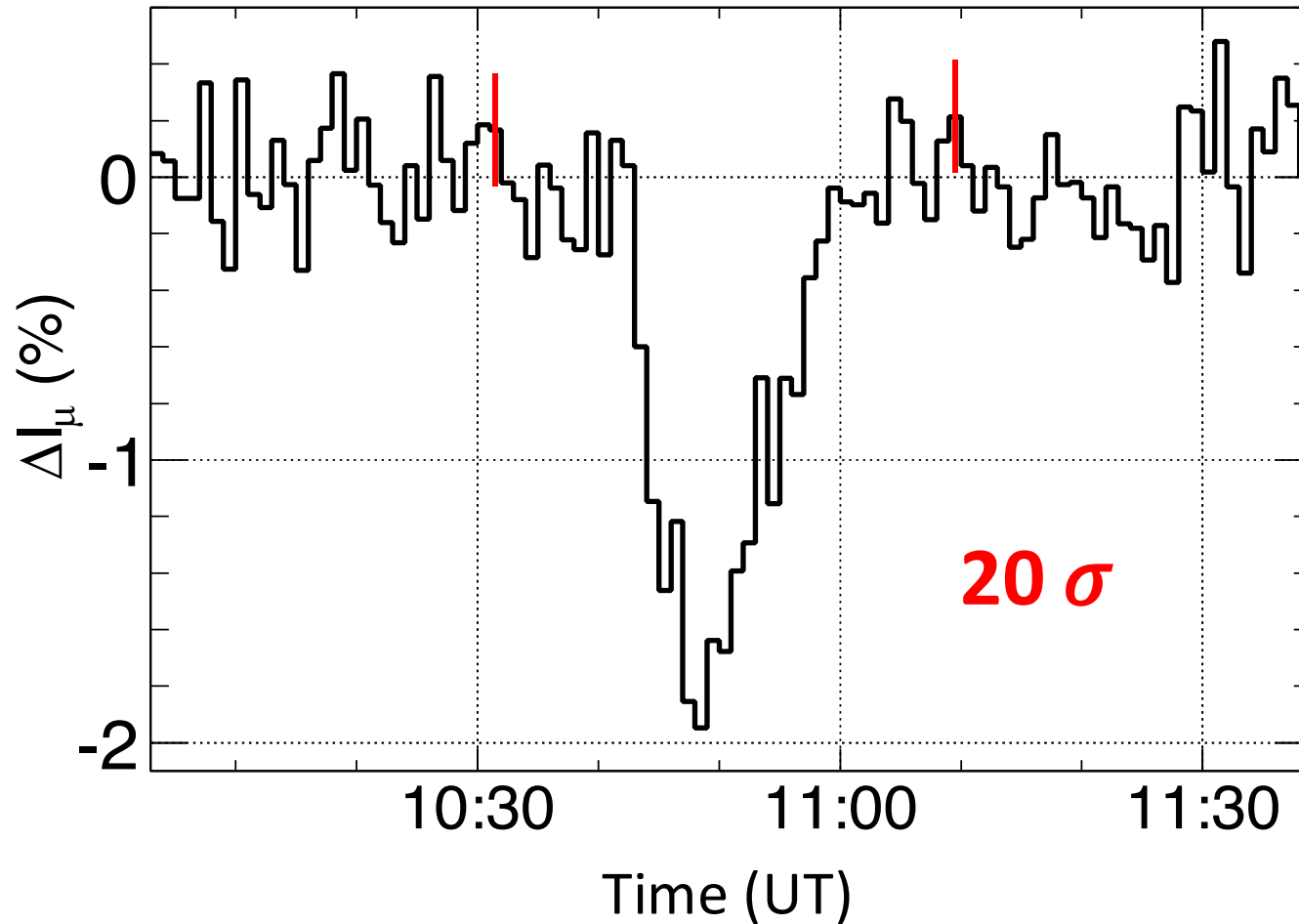


18 minutes

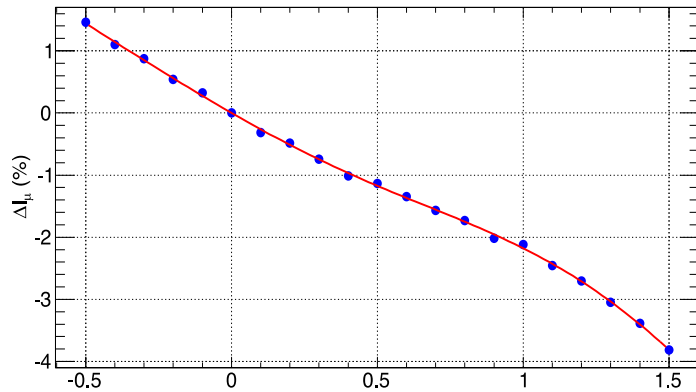
45 directions



Muon Intensity Variation

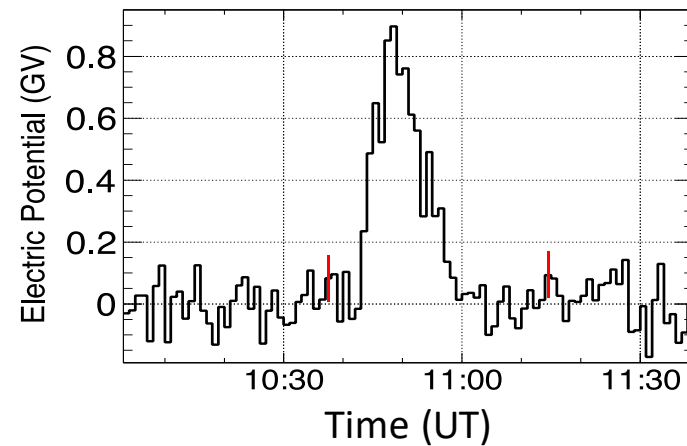
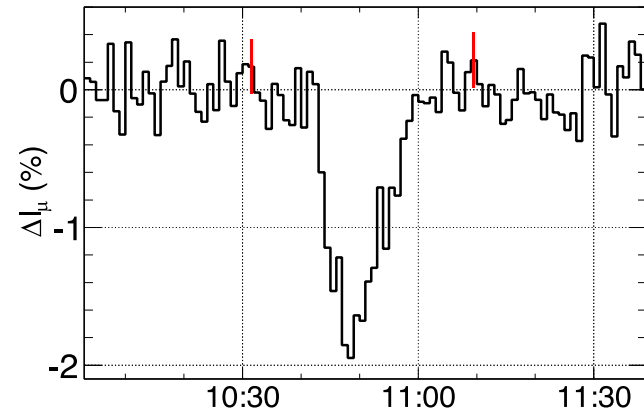


Monte Carlo Simulation



Electric Potential (GV)

- $\Delta I_{\mu(\text{Peak})} = (-2.0 \pm 0.2) \%$
- $V_{\text{Peak}} = (0.90 \pm 0.08) \text{ GV}$



Cloud Movement

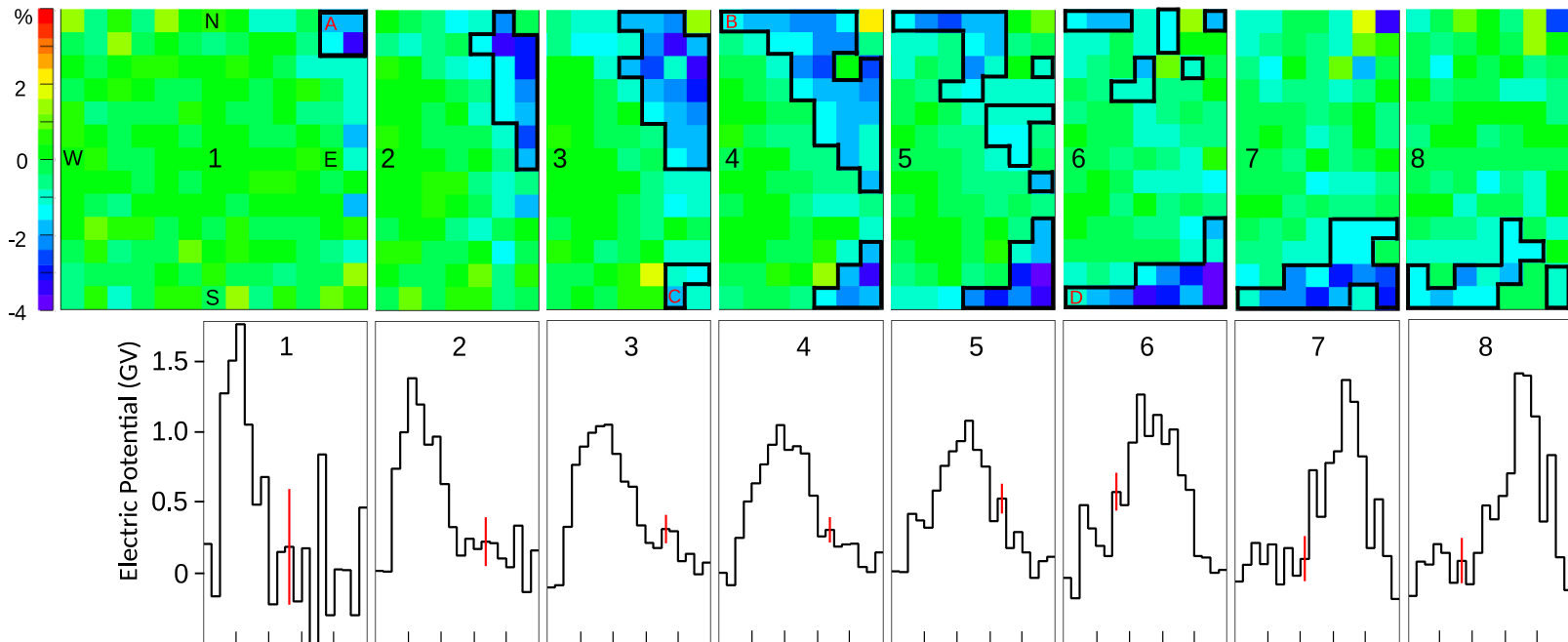


Image	Dir	V (GV)	Image	Dir	V (GV)
1	4	1.8	5	28	1.1
2	12	1.4	6	23	1.2
3	23	1.0	7	16	1.3
4	32	1.0	8	13	1.4

Mean V = 1.3 GV

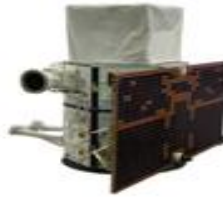
B. Hariharan et al., PRL 122, 105101 (2019)
 (Focus article & Editors' suggestion)

Timeline



1750s

Detection of
100 MeV γ -ray in
TGFs



1990s

Measurement of
1.3 GV



2019

1920s



C.T.R. Wilson's
prediction of
1GV 90Y ago

2000s



Measurement of
0.13 GV

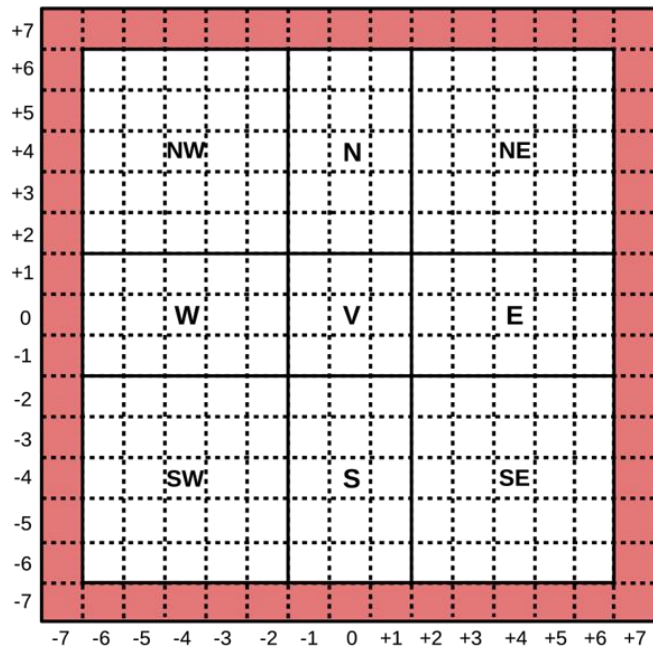
Event Statistics

Year	# of Events
2011	49
2012	43
2013	40
2014	52
2015	46

Year	# of Events
2016	18
2017	49
2018	48
2019	88
2020	54

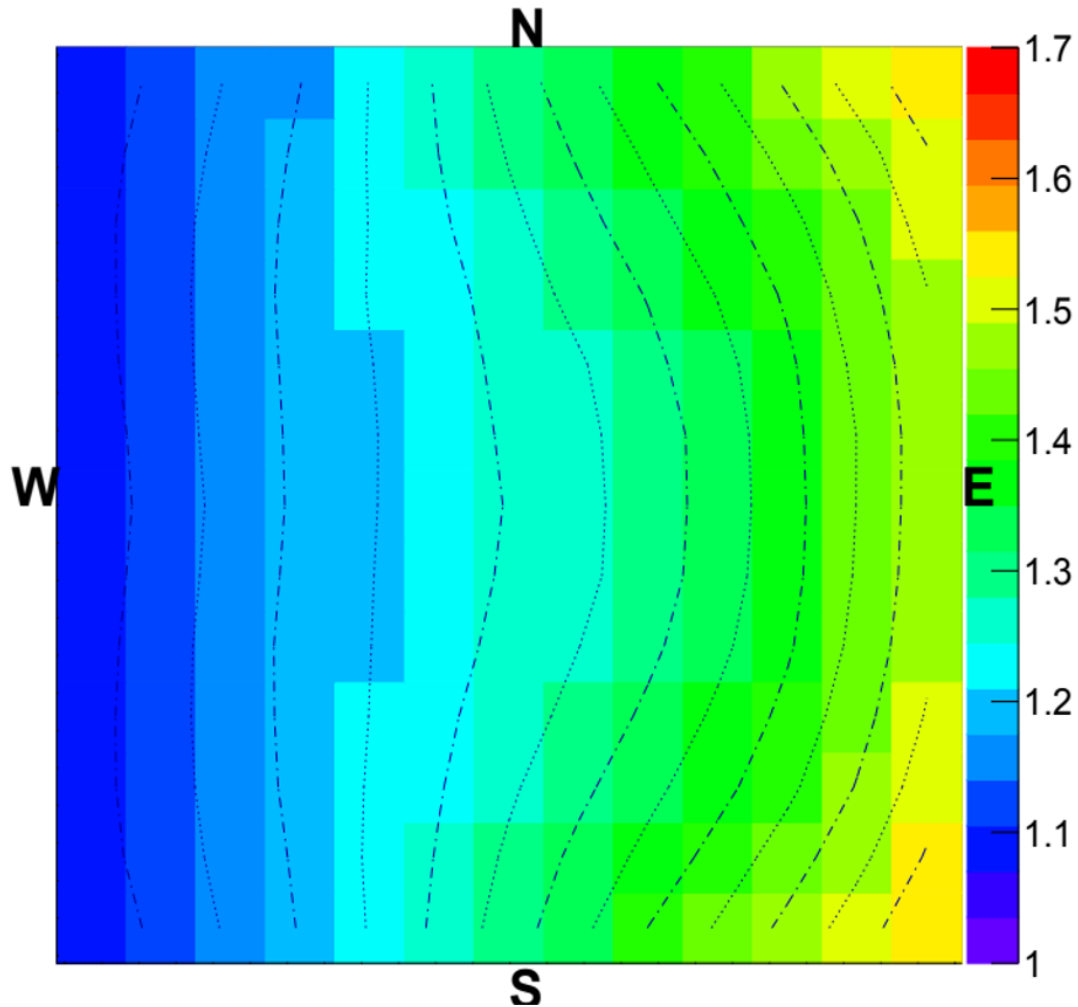
Total Events = 487

Angular Distribution of Events



6.2% (NW)	1.8% (N)	30.1% (NE)
0.6% (W)	0.2% (V)	2.8% (E)
7.0% (SW)	2.8% (S)	48.6% (SE)

Muon Charge Ratio (MC)



Dependence of Models

	FLUKA	GHEISHA	UrQMD
SIBYLL	0.90 —	1.07 (19%)	1.00 (11%)
EPOS-LHC	0.93 (3%)	1.07 (19%)	0.97 (8%)
QGSJETII	0.96 (7%)	1.12 (24%)	1.03 (14%)

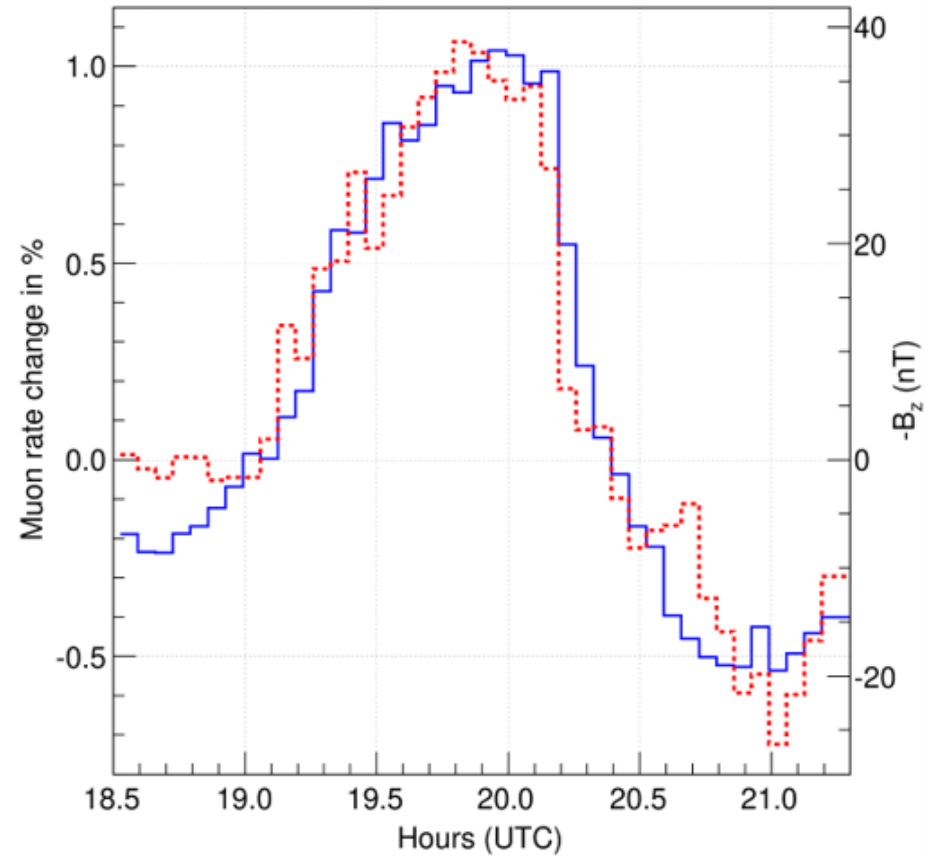
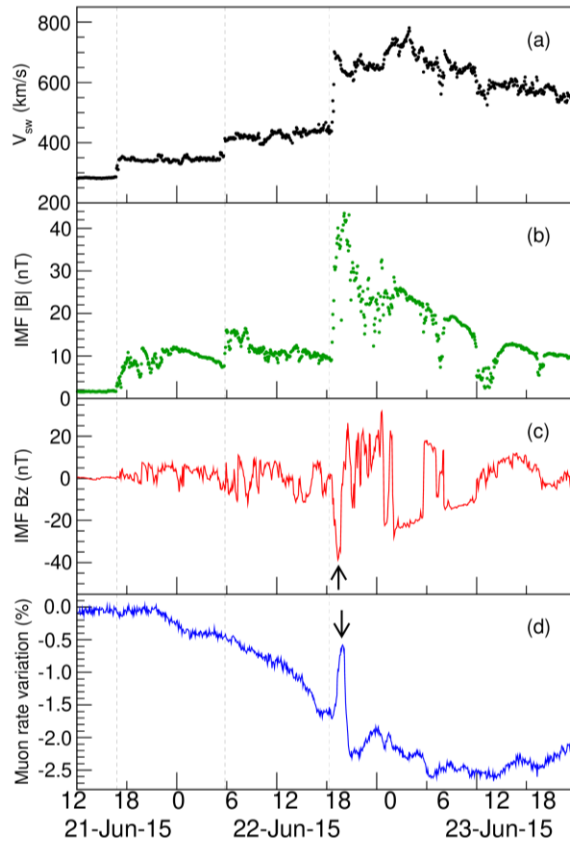
Summary - I

- Measured 1.3 billion volts in the cloud
- Measured various geometrical and electrical properties of the cloud
- Records about ~50 events / year.
- Asymmetry in angular distribution of events
- Supported by Monte Carlo simulations
- Conservative estimate using SIBYLL-FLUKA

Part II: Geomagnetic Storm Events

22 June 2015 Event

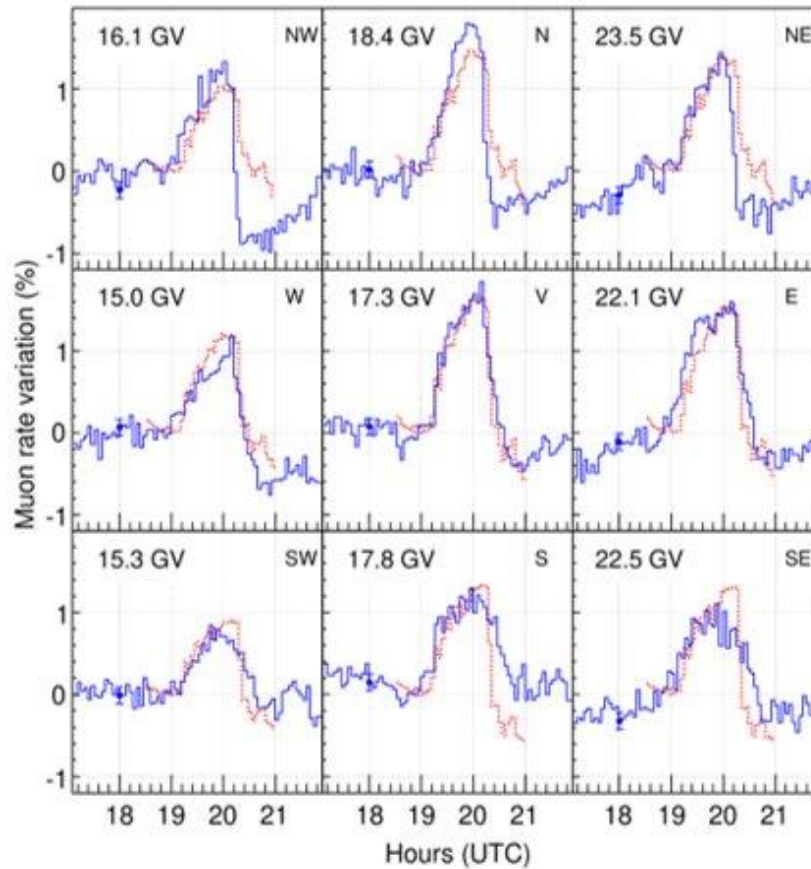
All Direction



P.K. Mohanty et al., PRL 117, 171101 (2016)

22 June 2015 Event

9-Direction



P.K. Mohanty et al., PRL 117, 171101 (2016)

GRAPES-3 Scintillators

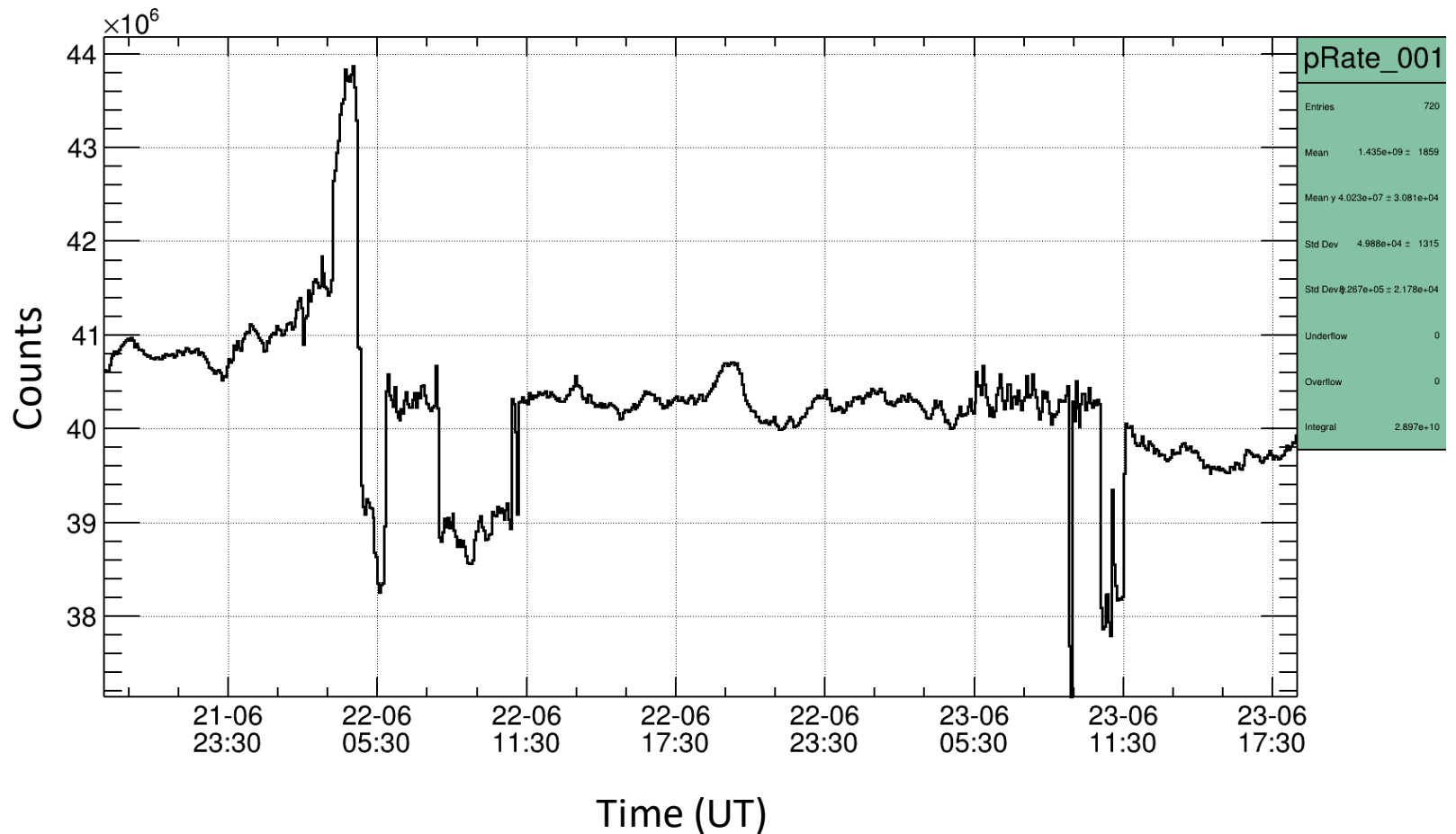


- Area 1 m² each
- Cone type
- Fiber type (Single PMT and Double PMT)
- 8 m inter-detector separation
- Total physical area 25000 m²
- ~3.6 million EAS

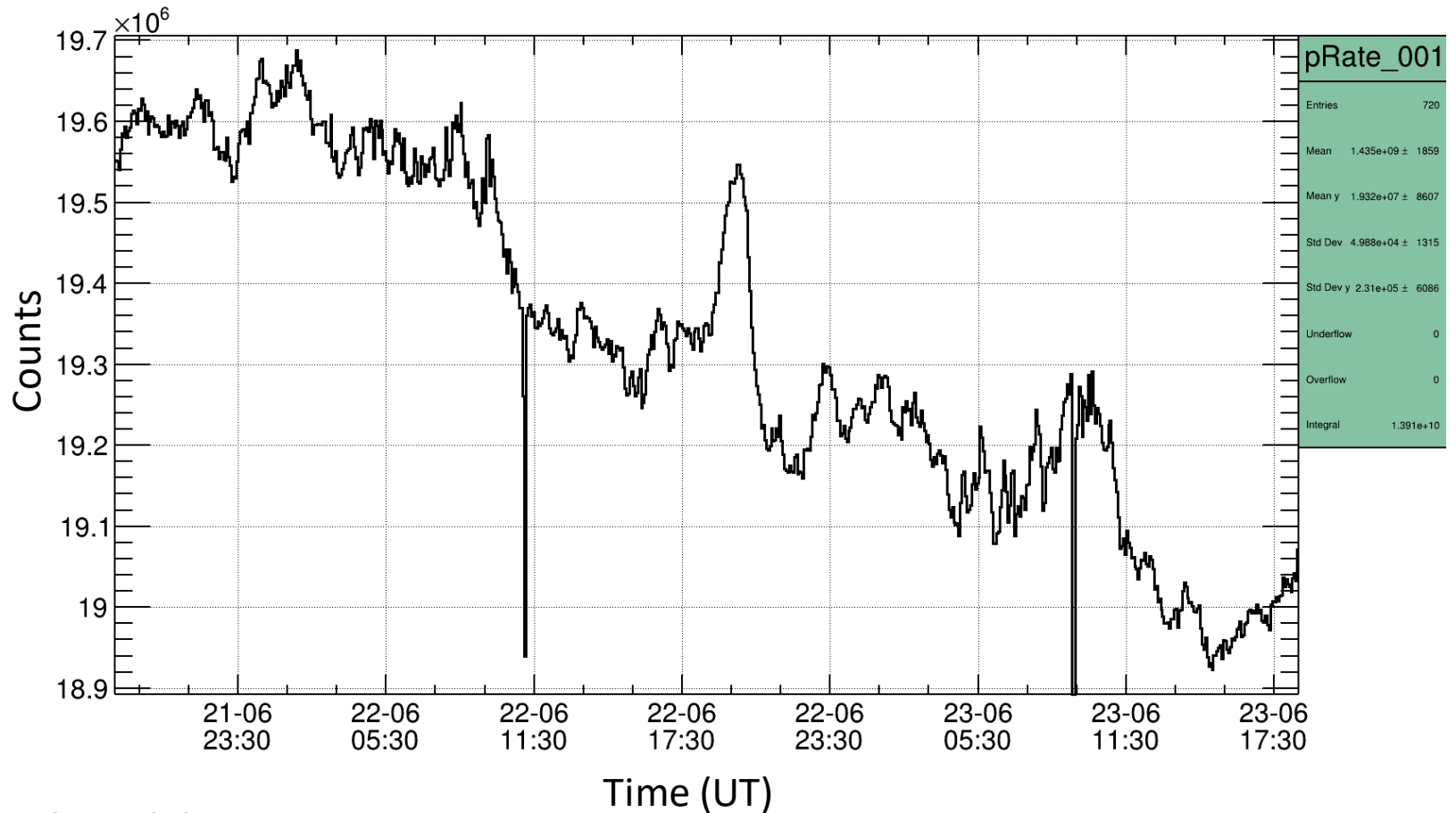
Comparison

Parameter	Muon Telescope	EAS Array
Type	Proportional counter	Plastic scintillator
Count	16	371
Area	35 m ²	1 m ²
Total area	560 m ²	371 m ²
Angular flux	Yes (169 direction)	No
Count rate	~48000 / sec	~100000 / sec
Threshold	1 GeV	Few MeV

All Detector Rate



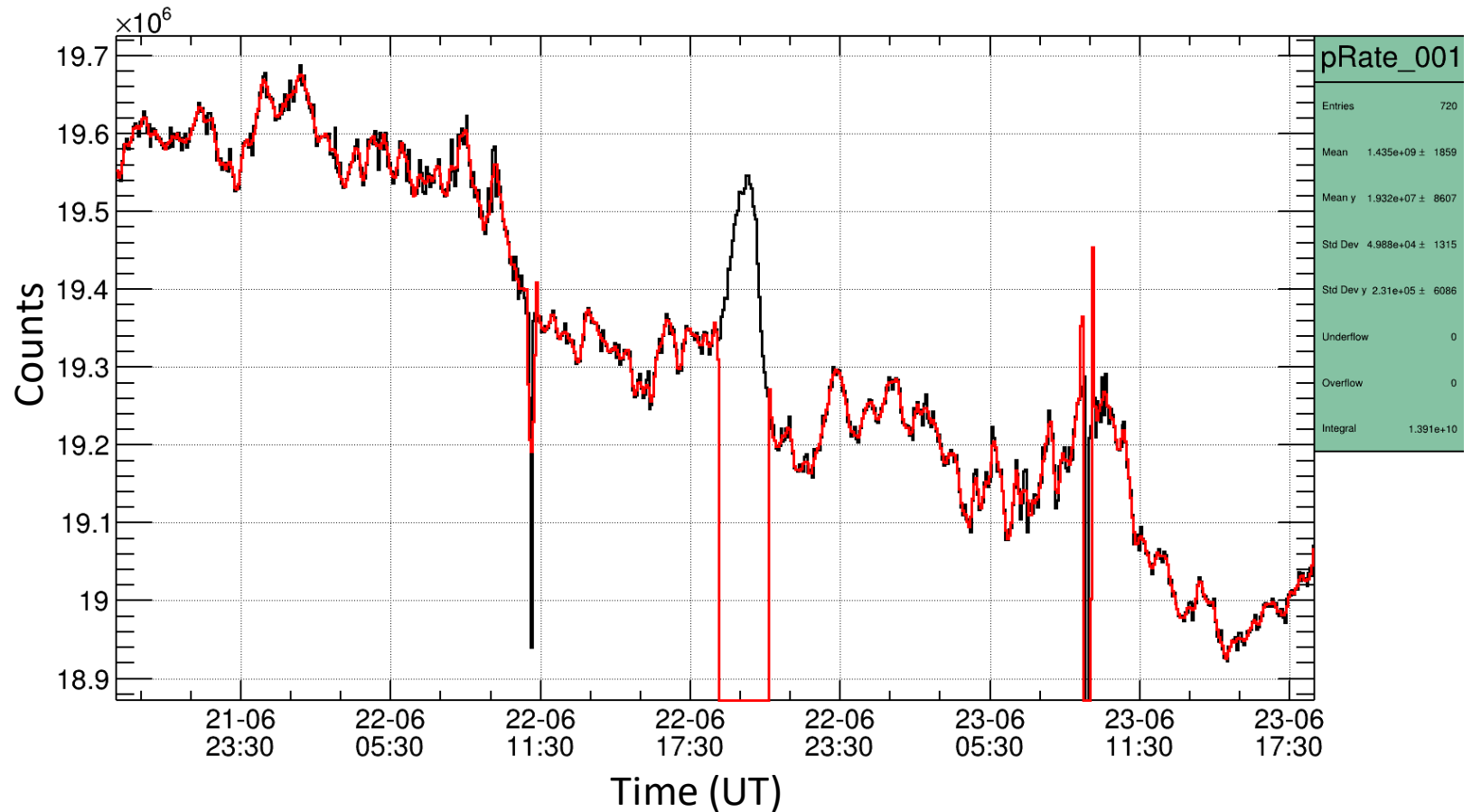
Good Detector Rate



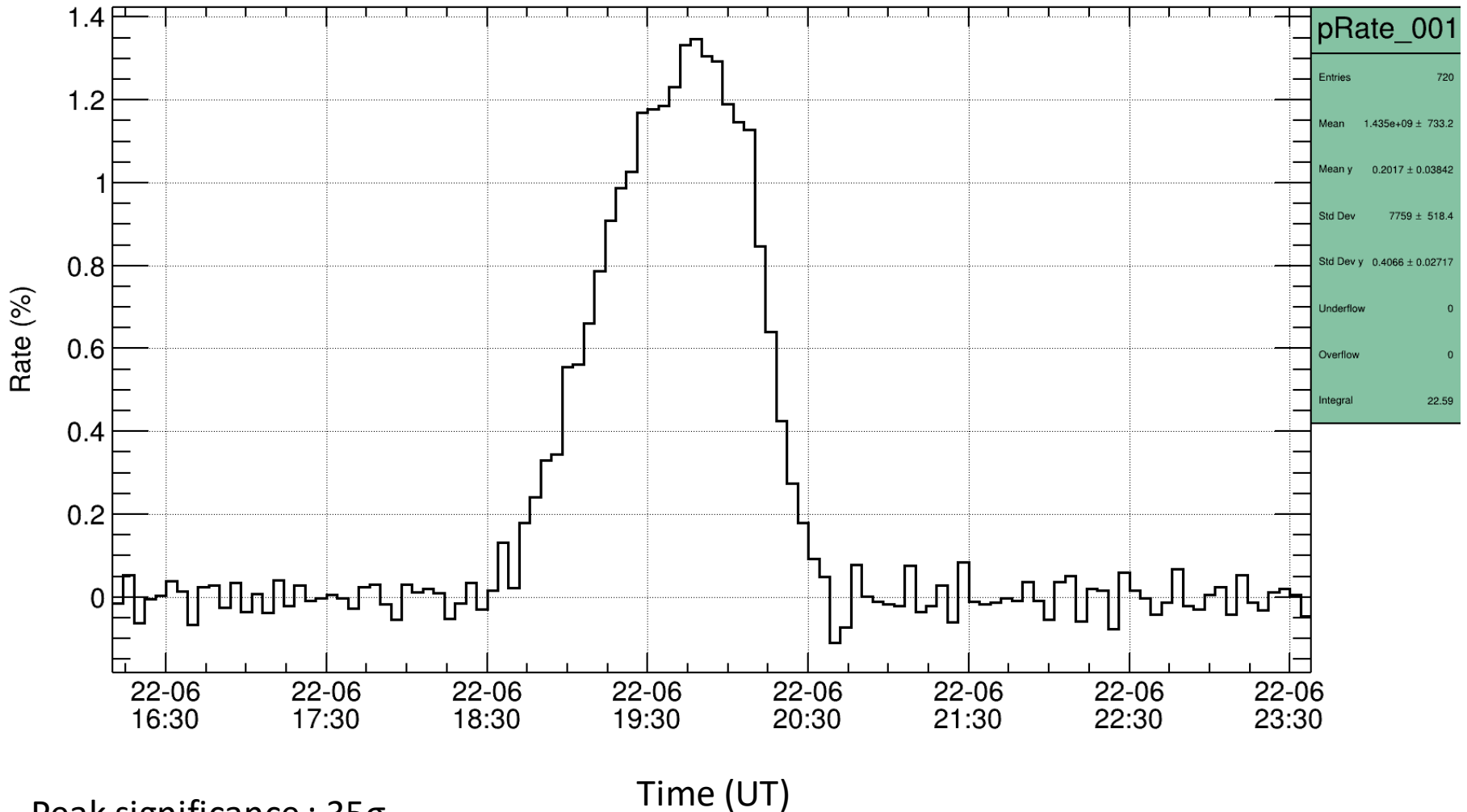
Selected detectors : 201

Savitzky-Golay Filter

Combination of moving average and higher order polynomial

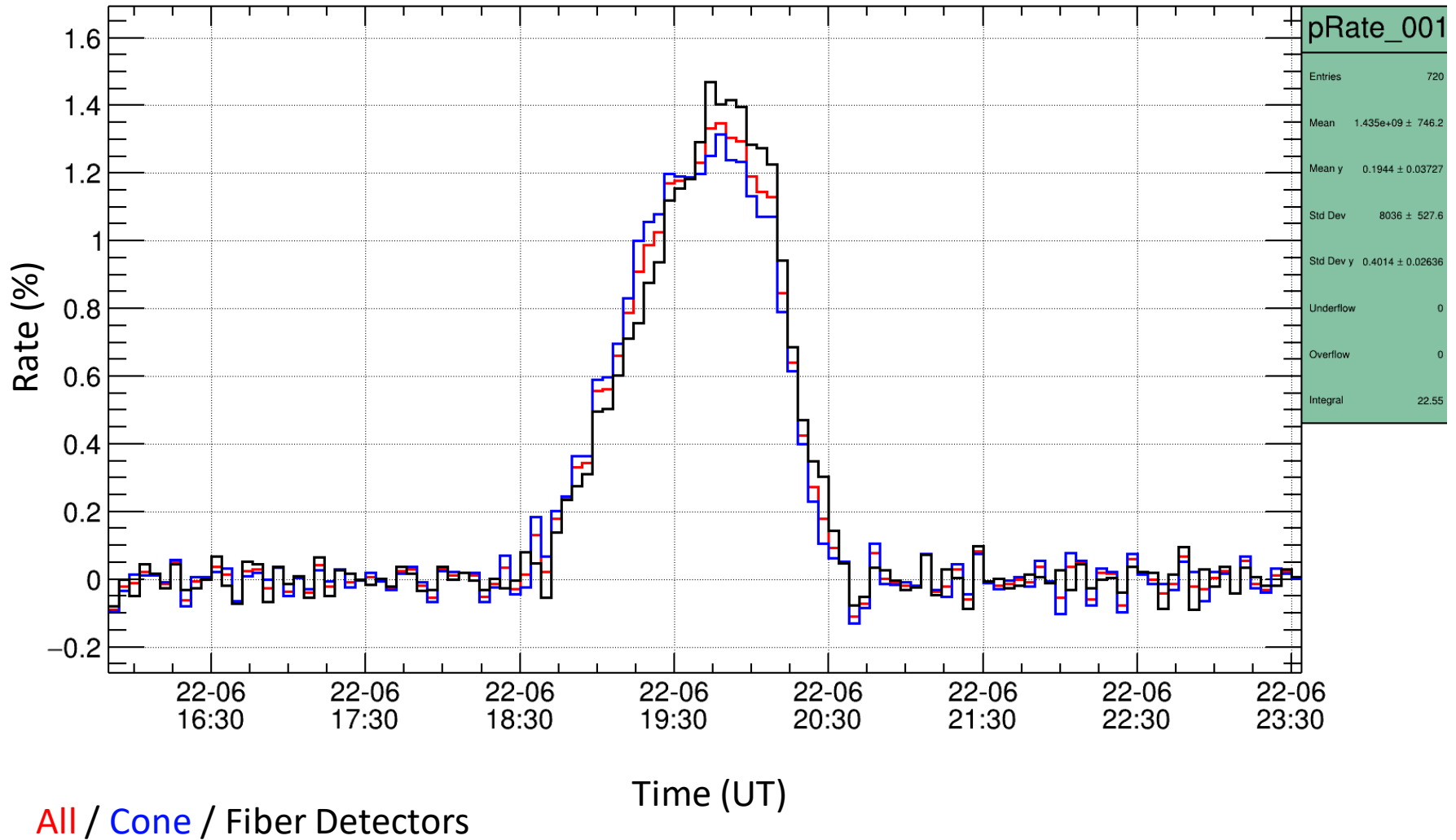


Background Corrected Rate

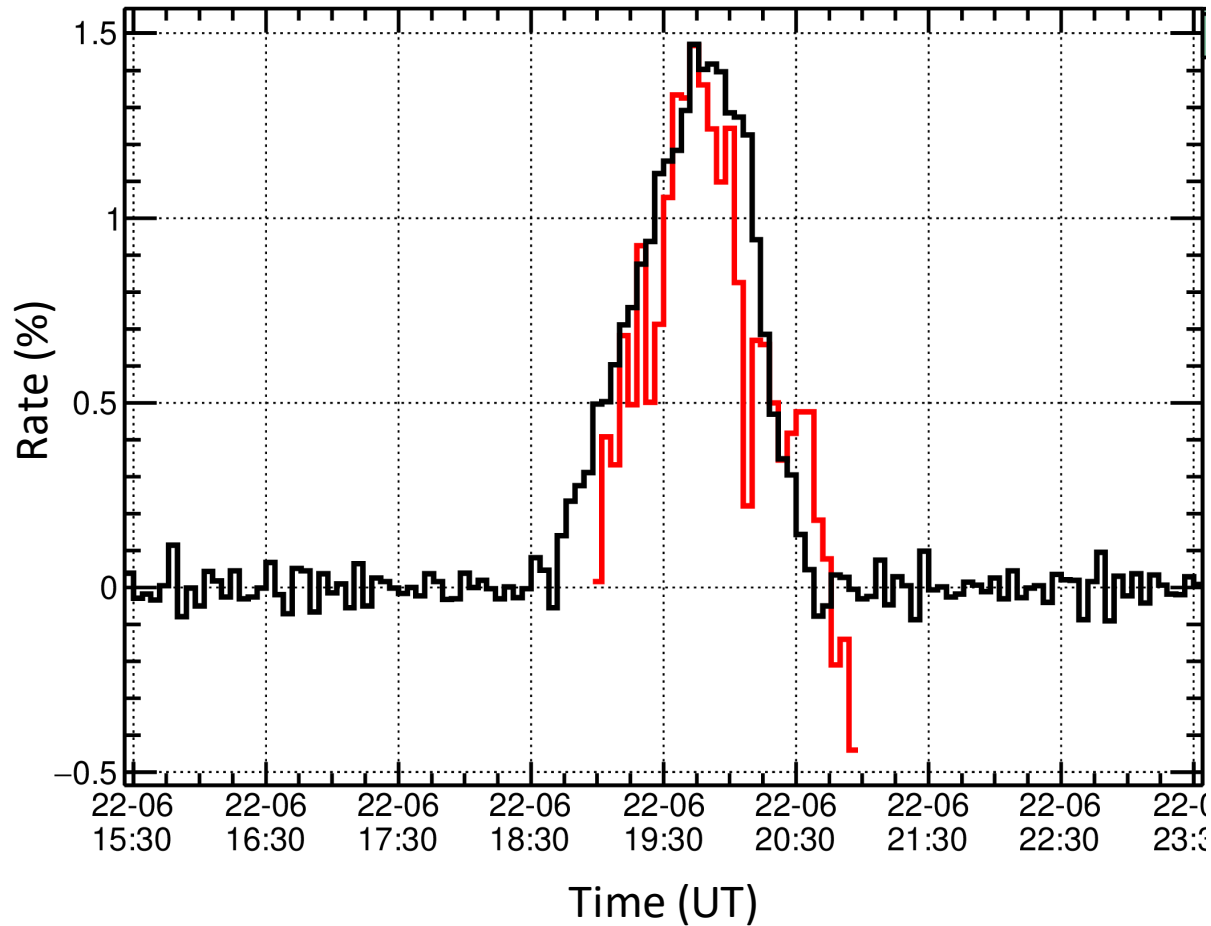


Peak significance : 35σ
Total significance : 103σ

Background Corrected Rate



Monte Carlo Simulation



Proton showers

$E = 10 \text{ GeV} - 10 \text{ TeV}$

Muon. : 58%

Electron : 26-29%

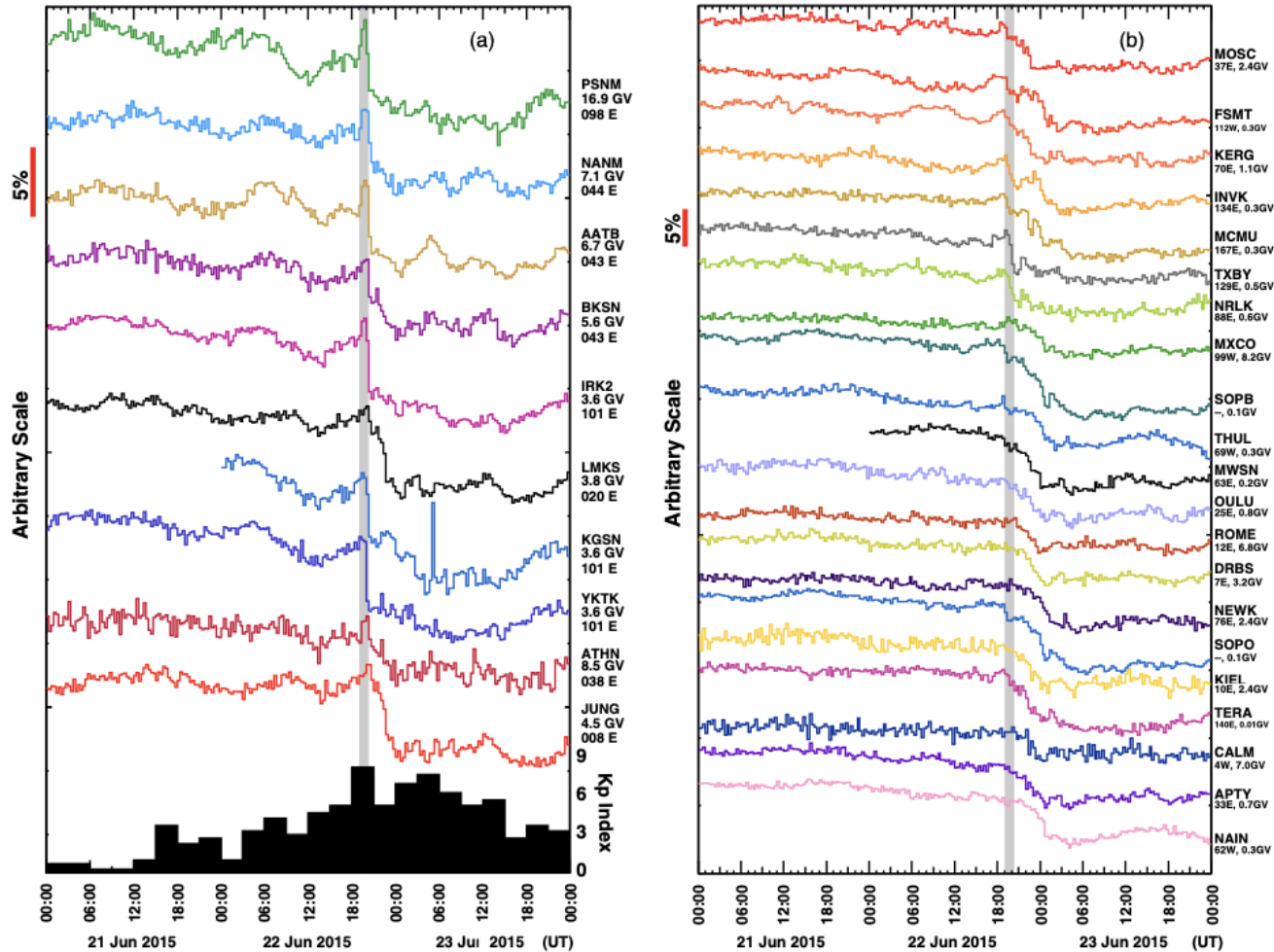
Gamma : 11-14%

Scaling. : 17

CC : 0.84

All / Cone / Fiber Detectors

Neutron Monitor Data



Summary - II

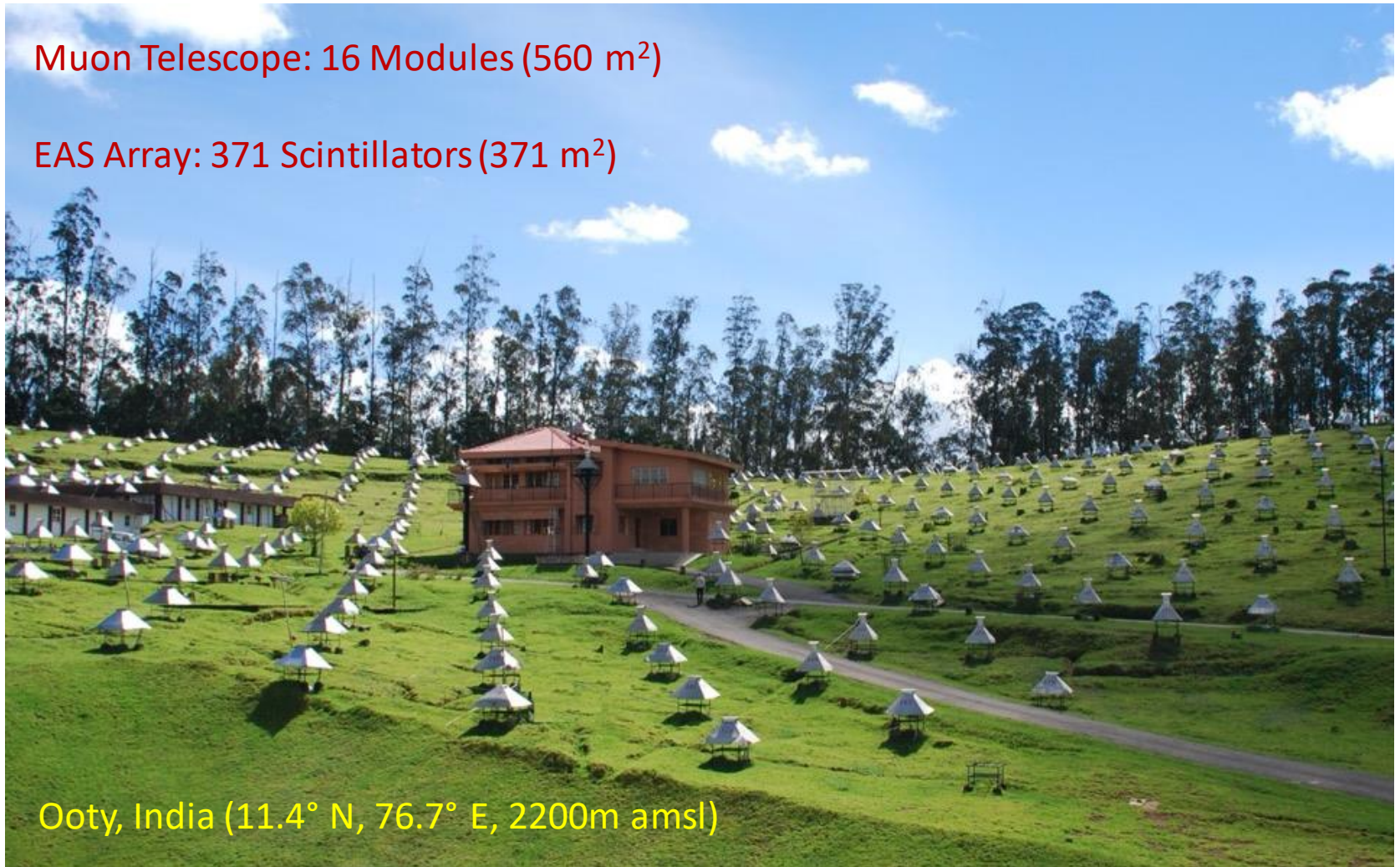
- GRAPES-3 scintillators provide vital information in understanding GMS.
- Better analysis methods are required to extract the signal over noisy background.
- The delay and scaling factor are consistent with muon telescope's observation.
- Preliminary simulations suggest the effect is reproduceable.
- New possibilities to find more weak events.

Thank You

Gamma Ray Astronomy at PeV Energies - 3

Muon Telescope: 16 Modules (560 m²)

EAS Array: 371 Scintillators (371 m²)



Ooty, India (11.4° N, 76.7° E, 2200m amsl)

Properties of the Cloud

- Mean $V = 1.3$ GV
- Lin. Vel. = 60 km hr^{-1}
- Ang. Vel. = $6.2^\circ \text{ min}^{-1}$
- Height = 11.4 km amsl
- Radius $\geq 11 \text{ km}$
- Area $\geq 380 \text{ km}^2$
- $C \geq 0.85 \mu\text{F}$
- $Q \geq 1100 \text{ C}$
- $E \geq 720 \text{ GJ}$
- $P \geq 2 \text{ GW}$

- Comparable to biggest nuclear reactor / hydroelectric / thermal power plants
- Enough to power a big town

B. Hariharan et al., PRL 122, 105101 (2019)
(Focus article & Editors' suggestion)

Large Area Muon Telescope

- 4 super-modules
- 4 modules per super-module
- 4 layers per module
- 58 proportional counters (PRCs) per layer
- Total: 3712 PRCs
- Area: 560 m²
- Energy threshold: $\sec(\theta)$ GeV by 2.4 m thick concrete absorber
- 169 directions covering 2.3 sr
- 4° angular resolution

